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Methods of modeling the power characteristics of wind turbines

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The work presents three methods of modeling the power characteristics of a wind turbine in the MATLAB & SIMULINK environment, that is – linear interpolation, nonlinear approximation, and linear approximation. Simulation tests were performed for two wind turbines: AH and AIRCON, with the nominal power of 10 kW. Calculations of the amount of electric energy generated by the above–mentioned types of wind turbines were performed for the constraint assumed (wind speed measurements in the south–eastern Poland for January and June 2014). The differences between the energy amounts calculated with the use of the three power characteristic modeling methods were determined. The results were summarized and final conclusions were formulated.

KEYWORDS: interpolation, approximation, wind turbine, MATLAB

1. Introduction

Research on technical installations used to transform the energy of wind into electrical energy has developed dynamically over the recent years. This is connected with the problem of environmental protection (the Kyoto Protocol [6]), diminishing fossil fuel supplies, as well as the continuously increasing demand for electrical energy.

The energy of wind belongs to the category of renewable resources which are rich in supply and highly available. Its changes are stochastic in nature which makes wind energy difficult to use in an efficient way. The level of power supplied to the grid by wind farms is not stable in time. A method which makes it possible to limit the negative effects of random characteristics of the operation of wind power sources is storing the energy and transferring it to the grid when wind speed decreases or declines to zero [27].

The amount of electrical energy generated in a wind turbine is a function of multiple factors, the most important of which are as follows: wind speed dependent on terrain roughness, altitude, and wind turbine power characteristics $P_{1i} = f(v_w)$ [17]. The turbine operates in varying values of the above–mentioned parameters. Both the stochastic contributory value (varying weather conditions) as well as the deterministic contributory value (the season of the year and the time of the day) influence wind speed values in time. The range of wind speed fluctuations is strictly determined for a given geographic location and season of the year. In Poland, average wind speed for the altitude of 10 m ASL ranges from 3 to 5 m/s, although its instantaneous values may be significantly higher or lower [30].

In Poland, the area characterized with the highest wind energy values is the Baltic Sea Coast and the north–eastern part of the country [18]. The average wind speed in this area reaches 5 *m/s*, and the yearly average wind speed exceeds 6 *m/s*. Figure 1 shows examples of the deterministic wind speed changes mentioned above during the day, throughout the year, and over the period of many years [30, 11, 20].

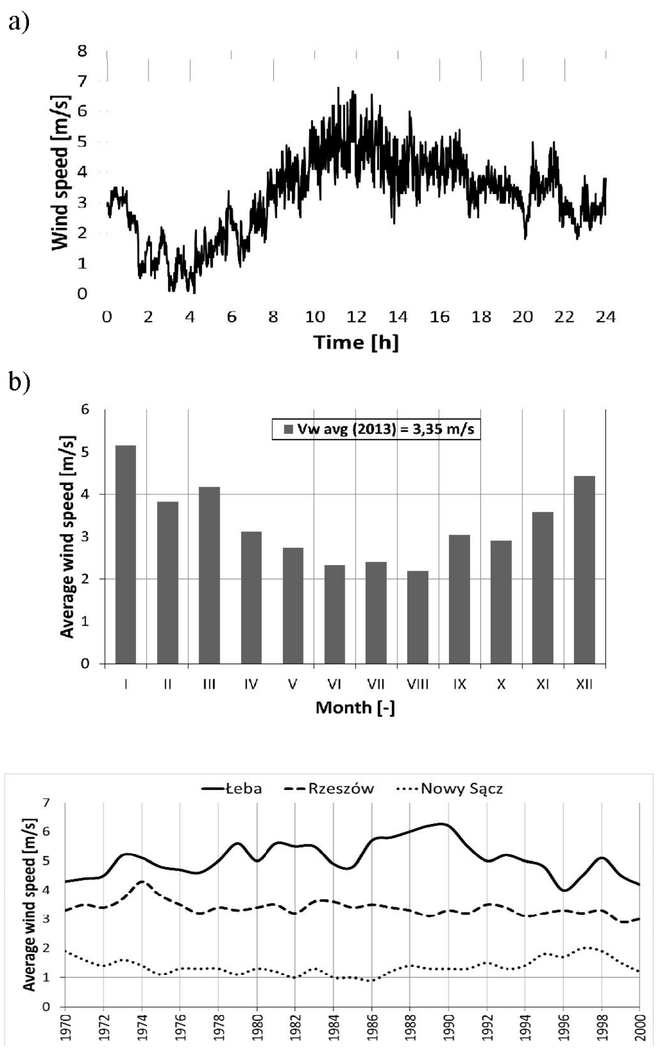


Fig. 1. Typical wind speed changes during: a) day, b) year, c) many years [30]

Daily wind speed fluctuations on 17 January 2014 (Figure 1a) and monthly average wind speed patterns for 2013 (Figure 1b) are presented on the basis of wind speed measurements performed by Krzysztof Markowicz, Ph.D., in the radiative transfer station in Strzyżów near Rzeszów.

Yearly wind speed values for Łeba, a city located in wind energy zone I (especially favorable), Rzeszów located in wind zone III (favorable), and Nowy Sącz located in zone V (unfavorable) are demonstrated (Figure 1c) on the basis of wind speed measurements provided by the Institute of Meteorology and Water Management (IMiGW) [30].

On the basis of research performed by IMiGW [30], the minimum average wind speed value for contemporary wind turbines is 4 *m/s*. Thus, it can be concluded that areas favorable in terms of wind energy production constitute more than half of the territory of Poland [18]. In accordance with the developing trend for designing turbines with low cut–in velocity requirements, areas with low wind speed values should not be excluded as unusable for the purpose of wind power production development [18].

2. Methods of modeling the power characteristics of a wind turbine

On the basis of an analysis of the scientific literature available [3, 5, 10, 16, 28], an overview of the methods connected with modeling the power characteristics of a wind turbine was performed. That was used as the basis for the application of three methods of turbine power curve modeling $P_{1i} = f(v_w)$ in the present work, with the use of interpolation and approximation. For the purpose of the work, three functional blocks intended for modeling the power characteristics of a wind turbine were developed in the Matlab environment.

Interpolation is the problem of identifying the function that goes exactly through the set points called interpolation nodes. Approximation, on the other hand, is the process of identifying approximate solutions on the basis of known solutions. The purpose of approximation is to adjust the coefficients of the approximating function in such a way so as to minimize the error function. It is not required for the approximating function that approximates the set function to go through specific points as in the case of interpolation.

In the first method (linear interpolation), linearization involving the identification of measurement points situated near the wind speed values was applied with the use of proportion. The turbine power vector and the corresponding wind speed vector were introduced to the *Linear wind turbine power curve* block for 43 wind turbines for which interpolated values were calculated with the use of the polygonal function method.

In the second method (nonlinear approximation), approximation involving the adjustment of the approximating function to the measurement points with the use of the least square method with the use of the exponential function was applied. The turbine power vector and the corresponding wind speed vector for which approximation coefficients were calculated were introduced to the *Non–linear wind turbine power curve* block. In the third method (linear approximation), measurement values were averaged so as to identify the parameters of the approximating function with the use of linear regression. The power characteristics of the turbines were introduced to the *Linear approximation wind turbine power curve* block in the form of power and wind speed vectors for which approximation coefficients were calculated.

3. The mathematical model of a wind turbine

A wind turbine is a complex structure consisting of mechanical, electrical, electronic (microprocessor) systems capable of transforming wind energy into mechanical power and, finally, into electrical power. Currently, the most frequently used type of converters are those with horizontal axis of rotation and with three–bladed rotors [1, 18]. Wind turbines of varying power capacity (from a few W up to a few MW) are designed for operation in autonomous systems [21] as well as in the grid [7, 17, 22].

Electric power production in wind turbines takes place within the range from activation velocity v_{cut-in} (cut–in velocity) to deactivation velocity $v_{cut-out}$ (cut–out velocity). The output power value P_{1i} of a wind turbine is the function of wind speed v_w presented in the form of power characteristics $P_{1i}(v_w)$ [27]. The value of the electric energy generated by the wind turbine A over a set period of time with the sampling period of Δt_w is determined on the basis of its power P as a function of the wind speed v_w in accordance with the following dependency:

$$A = \sum_{i=1}^{N} P_{1i}(v_w) \cdot \Delta t_w \tag{1}$$

In connection with the structural differences in the construction of wind turbines, their power characteristics may differ despite identical nominal power values, which results in the fact that they generate different electric power amounts at the same wind speed. Figure 2a shows fragments of $P_{1i}(v_w)$ characteristics for wind speed values between 0 and 10 *m/s* for wind turbines of the AH and AIRCON types characterized with identical nominal power of P_{1N} = 10 *kW*. The differences in the power values for both turbines for the wind speed range provided above amount to 40%, which is a high value with considerable influence on the level of electric power produced. Figure 2b presents power characteristics $P_{1i}(v_w)$ of the above–mentioned turbine types. As a result of the shift in the power characteristics of the AIRCON turbine towards lower wind speed values, the amount of electric power that it generates is higher than the amount produced by the AH turbine in the areas with lower wind speed values [27].

The cut–in velocity that can be read from the characteristics of both turbines is 2,5 m/s (AH) and 2,5 m/s (AIRCON), respectively, and the cut–out velocity is 30 m/s (AH) and 32 m/s (AIRCON). As it can be read from the power characteristics of both turbines, the value of the output power generated stabilizes for wind speed values ranging from 12 to 25 m/s. This phenomenon is connected with the adjustment of the blade positioning angle, which impacts the lift and the braking force operating on the rotor blades, maintaining the rotational speed of the rotor at a constant level. During a wind gust, the regulator reduces the blade positioning angle, which, in turn, reduces turbine rotation and protects it against permanent damage. As a result, the loads on the rotor as well as the mechanical system are reduced which makes the power characteristics more even [8].

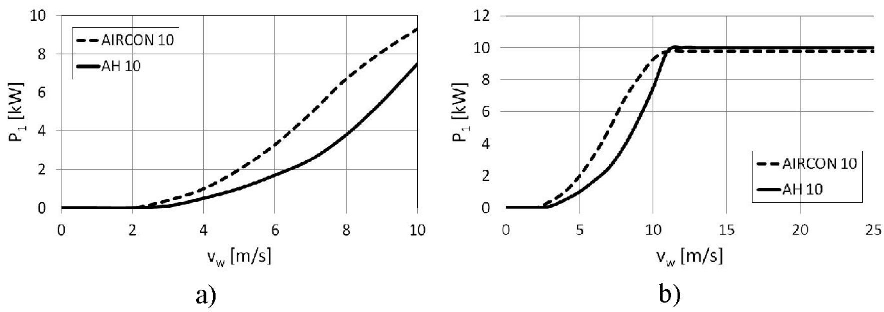


Fig. 2. Power characteristics of the wind turbines used in the studies: a) initiation section (wind speed range from 0 to 10 *m/s*), b) mutual positioning (from 0 to 25 *m/s*) [4]

Modeling a wind power plant encompasses: the wind turbine, the powertrain, the generator, the converter system, and the control system [17, 29]. In the present work, a model of a wind turbine of linear and nonlinear characteristics, in which completion of the full simulation of the turbine operation process and analysis of its dynamic states are not required, is proposed. For known wind speed fluctuations at a given geographic location, the response of the wind turbine in the form of the output power generated is consistent with its power characteristics $P_1(v_w)$. The calculation model used for that purpose includes a simulation of wind turbine operation and an analysis of electric power production [27].

4. The simulation model of a wind turbine

On the basis of the available scientific literature [17, 18, 27] and technical standards [23, 24, 25, 26], a model of a wind turbine (Figure 2) implemented in the Matlab & Simulink environment version R2014a was developed. The model makes it possible to conduct an analysis of the operation of the wind turbine in which the output power is controlled in a linear and nonlinear way. The work presents simulation results for three methods of modeling wind turbine power characteristics in accordance with chapter 2 of the present work.

The equivalent diagram of the system includes blocks representing: constraint (wind speed v_w changes in time) – the *Repeating Sequence Interpolated* block, wind system power characteristics modeling – *Linear wind turbine power curve*, *Non–linear wind turbine power curve*, *Linear approximation wind turbine power curve*, elements connected with the determination, transformation and calculation of output parameters *Integrator*, *Gain* blocks, and their visualization – *Display*, *Scope*, *To Workspace* blocks. Two multiplexers with three inputs and one output – *Mux* block, were used to select power and wind speed vector signals from two turbines in three modeling methods. One two–channel multiplexer with one input and three outputs – *Demux* block, was used to select turbine power vector signals. Data from the text file was inserted into a vector containing nearly 55000 measurement samples for January and June with the time step of 47 seconds. Wind speed measurements from the period of two months (January and June 2014) performed by Krzysztof Markowicz, Ph.D. in the radiative transfer station in Strzyżów near Rzeszów were used as the constraint in the simulation process of the operation of AH and AIRCON wind turbines. Additionally, a set of functions and scripts connected with the calculation block development procedures for each of the three methods used was created in the MATLAB environment language. The block diagram of the wind turbine model including the measurement, calculation, and visualization blocks created in the MATLAB & SIMULINK environment is presented on Figure 3.

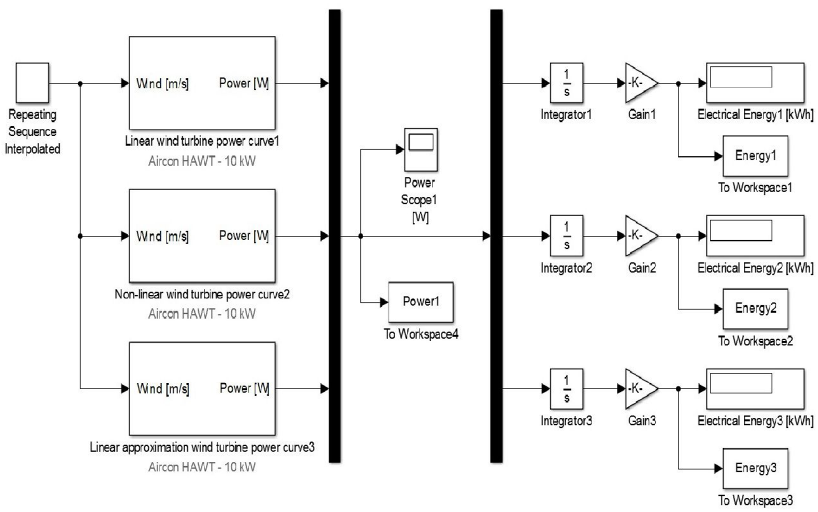


Fig. 3. Block diagram of the wind turbine model created in the SIMULINK environment

Two wind turbines with horizontal axis of rotation – AH and AIRCON, with the technical parameters provided below in Table 1, were used in the simulation tests in the SIMULINK environment.

Table 1. Technical parameters of the wind turbines used in the simulations in SIMULINK environment [4]

No	Parameter Name	Symbol	AH	AIRCON
1	Nominal power	P_{1N} [kW]	10,0	10,0
2	Cut–in velocity	$v_{cut\text{–}in}$ [m/s]	2,5	2,5
3	Nominal velocity	v_n [m/s]	11,0	11,0
4	Cut–out velocity	$v_{cut\text{–}out}$ [m/s]	30,0	32,0
5	Max wind speed for WT	v_{max} [m/s]	60	50
6	Max rotational velocity	$v_{r\ max}$ [obr/min]	180	130
7	Rotor diameter	d_w [m]	7,8	7,1
8	Number of blades	n [–]	3	3
9	Sweeping area	S [m^2]	47,8	39,6
10	Output DC voltage	U_{DC} [V]	400	400

5. Simulation of wind turbine operation with real constraint

Tables 2a to 2d present calculation results of the amount of electric power *A* produced by the turbine types mentioned above in January and June 2014 with the use of linear interpolation (method I), nonlinear approximation (method II), and linear approximation (method III). As a result of the analysis, electric power amount differences between the turbines $\Delta A_{\%}$ as well as electric power amount differences for each of the turbines with the use of different power curve modeling methods were determined in accordance with the following dependency:

$$\Delta A_{\%} = \frac{A_{AIRCON} - A_{AH}}{A_{AIRCON}} \cdot 100\% \tag{2}$$

Table 2a. Simulation results for method I – linear interpolation, II – nonlinear approximation and III – linear approximation (*A* – electric power production in January, $\Delta A_{\%}$ – electric power amount differences between the turbines)

No	Method used	AH	AIRCON	$\Delta A_{\%}$
		Electric power production A [kWh/January]		[%]
1	I	1250,7	1891,0	33,9
2	II	1245,2	1889,0	34,1
3	III	1340,9	1958,0	31,5

Table 2b. Simulation results for methods I, II, and III ($\Delta A_{\%}$ – electric power amount differences for each of the turbines in January depending on the method used)

No	Method comparison	AH			AIRCON		
		Electric power production A [kWh/January]		$\Delta A_{\%}$ [%]	Electric power production A [kWh/January]		$\Delta A_{\%}$ [%]
1	I – II	1250,7	1245,2	0,4	1891,0	1889,0	0,1
2	II – III	1245,2	1340,9	7,1	1889,0	1958,0	3,5
3	I – III	1250,7	1340,9	6,7	1891,0	1958,0	3,4

Table 2c. Simulation results for methods I, II, and III (A – electric power production in June, $\Delta A_{\%}$ – electric power amount differences between the turbines)

No	Method used	AH	AIRCON	$\Delta A_{\%}$ [%]
		Electric power production A [kWh/June]		
1	I	293,6	645,0	54,5
2	II	310,6	641,2	51,6
3	III	291,2	712,6	59,1

Table 2d. Simulation results for methods I, II, and III ($\Delta A_{\%}$ – electric power amount differences for each of the turbines in June depending on the method used)

No	Method comparison	AH			AIRCON		
		Electric power production A [kWh/June]		$\Delta A_{\%}$ [%]	Electric power production A [kWh/June]		$\Delta A_{\%}$ [%]
1	I – II	293,6	310,6	5,5	645,0	641,2	0,6
2	II – III	310,6	291,2	6,2	641,2	712,6	10,0
3	I – III	293,6	291,2	0,8	645,0	712,6	9,5

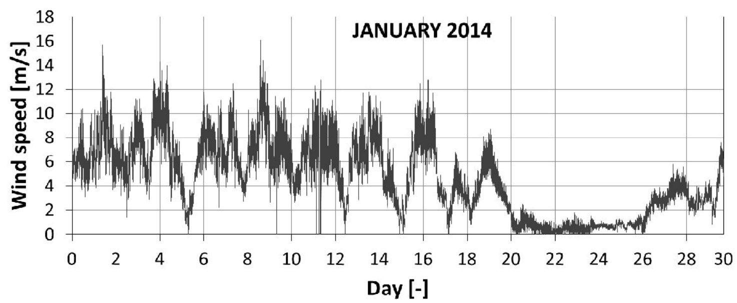
Table 3 presents simulation time results for methods I, II, and III.

Table 3. Simulation time results for methods I, II, and III in January and June

No	Method	AH		AIRCON	
		Simulation time [seconds/ January]	Simulation time [seconds/ June]	Simulation time [seconds/ January]	Simulation time [seconds/ June]
1	I	387	380	378	374
2	II	370	375	371	369
3	III	377	376	382	377

As a result of the analysis of wind speed fluctuations for the geographic location provided in point 4, the following values were determined: wind speed fluctuations in January and June 2014 (Figure 4), turbine power production $P_1(v_w)$ fluctuations (Figures 5 and 6), electric power A fluctuations on: 17 January and 17 June 2014 (Figures 7 and 8). Monthly electric power production as a function of the day number, as the amount of energy produced and cumulated over consecutive days in January and June is presented on Figures 9 and 10. Simulation time distribution as a function of the method number in January and June 2014 is presented on Figure 11.

a)



b)

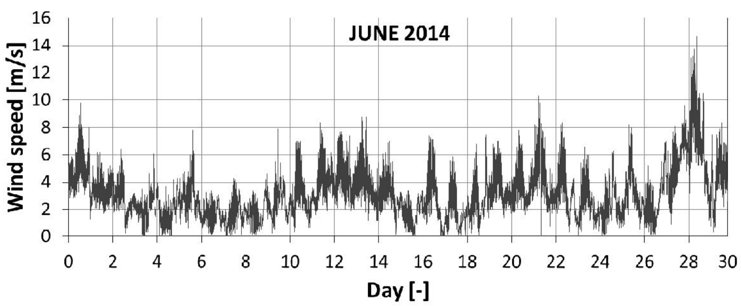
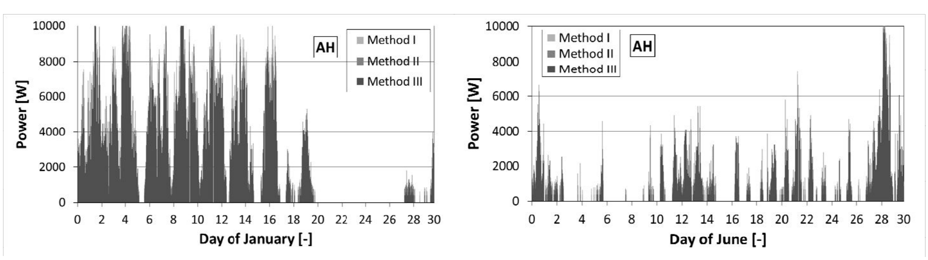
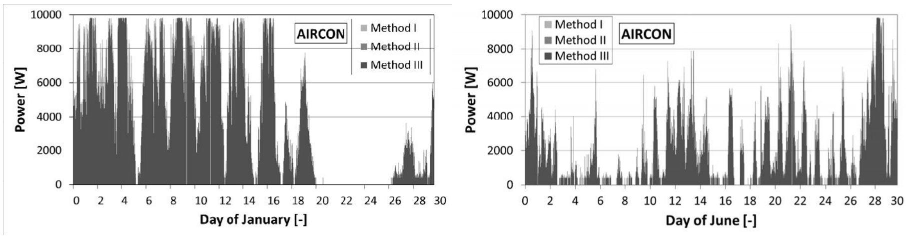


Fig. 4. Wind speed fluctuations as a function of the number of day in:
a) January 2014, b) June 2014



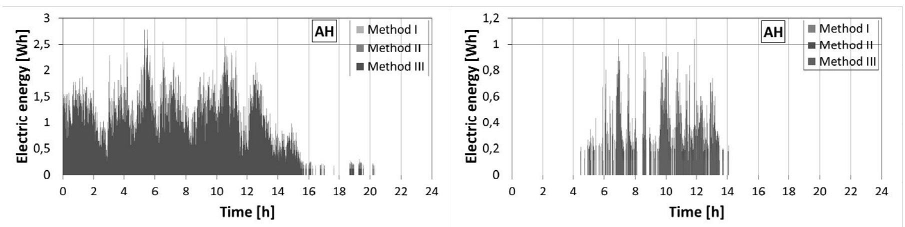
a) b)

Fig. 5. Power P_{1i} generation fluctuations in AH turbine in: a) January 2014, b) June 2014



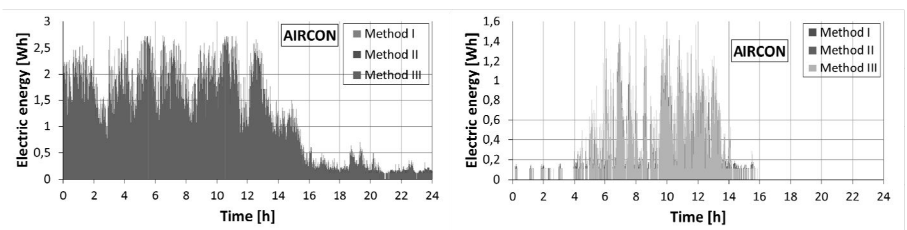
a) b)

Fig. 6. Power P_{1i} generation fluctuations in AIRCON turbine in:
a) January 2014, b) June 2014



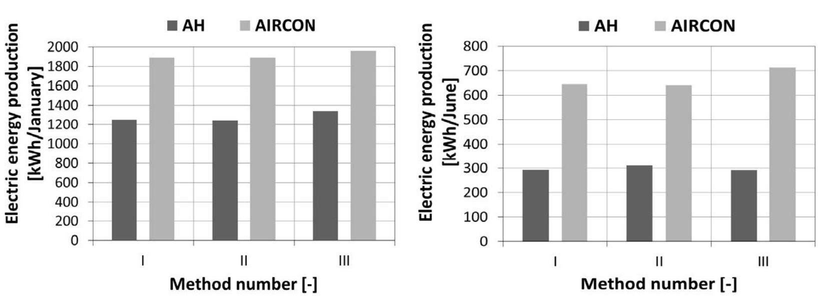
a) b)

Fig. 7. Electric energy production A fluctuation in AH turbine on:
a) 17 January 2014, b) 17 June 2014



a) b)

Fig. 8. Electric energy production A fluctuation in AIRCON turbine on:
a) 17 January 2014, b) 17 June 2014



a) b)

Fig. 9. Electric energy production A as a function of the method number in:
a) January 2014, b) June 2014

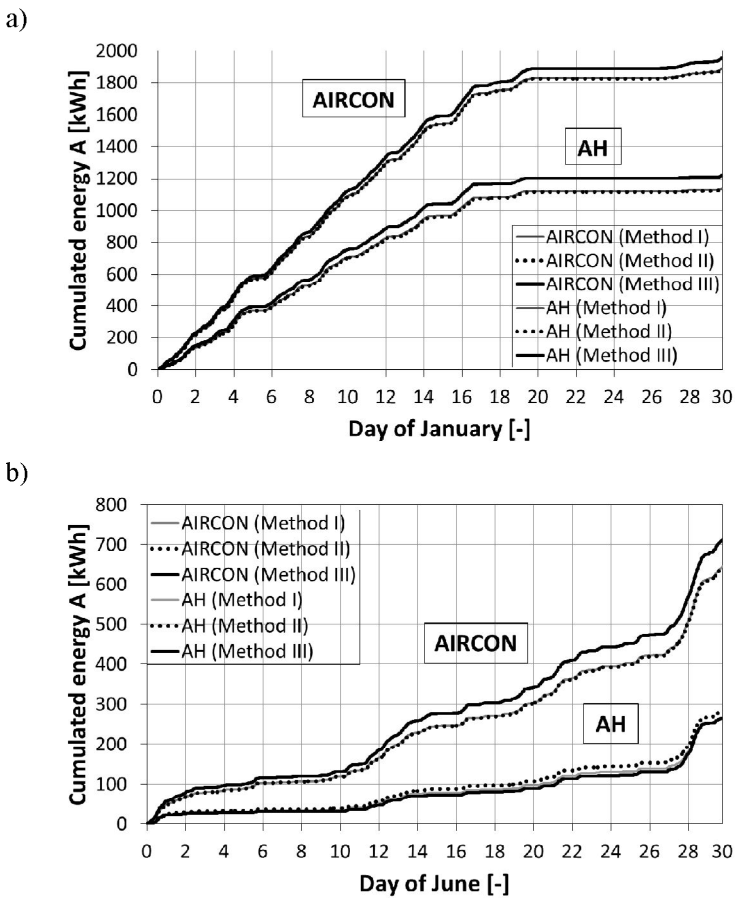


Fig. 10. Electric energy production during the month (cumulated value)
a) January 2014, b) June 2014

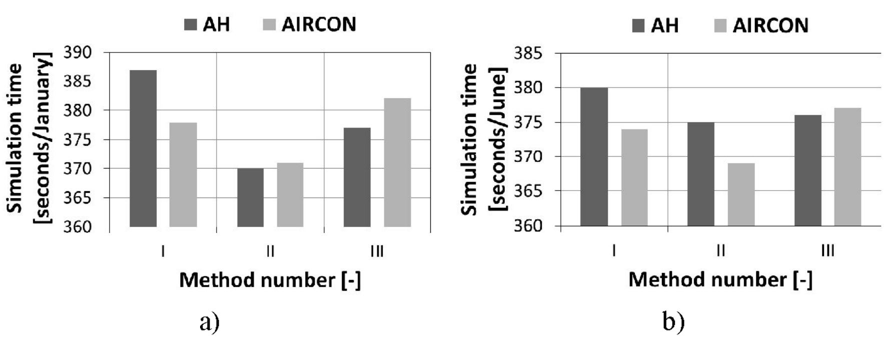


Fig. 11. Simulation time distribution as a function of the method number in:
a) January2014, b) June 2014

6. Conclusion

The work presents the application of the MATLAB & SIMULINK environment to simulate the operation of wind turbines in real constraint conditions with the use of three methods of turbine power curve modeling. The study conducted confirmed the differences in electric energy production resulting from the methods of modeling the power characteristics of wind turbines that are used. Simulation was performed for three modeling methods, that is – linear interpolation (method I), nonlinear approximation (method II), and linear approximation (method III). Simulation studies were conducted for two wind turbines: AH and AIRCON, with the nominal power of 10 kW. Real constraint (wind speed measurements in the area of south–eastern Poland for January and June 2014) was introduced into the model. As a result of the simulation, electric energy production A by the turbines was determined. On the basis of the study, the differences in the amount of electric energy generated by both turbines reaching up to 35% in January and up to 60% in June were determined. On the basis of the analyses of electric energy amounts between the two methods used, energy differences at the level of up to 7% in January and up to 10% in June were detected for each of the turbines. The purpose of the methods presented in the present work was the speed and the precision in the calculation of the task performed. Both of those conditions were met only in method II (nonlinear approximation) and, thus, it can be considered as the best of the three. The study showed that two turbines with the same nominal power working in the same real constraint conditions generate different electric energy amounts and that the differences between them exceed 50%. This means that the selection of a turbine that is appropriate for a given geographic location is essential.

Establishing the wind power resources for a given geographic location is a complex process. This results from the stochastic nature of wind speed distribution that was mentioned above, which is additionally influenced by three types of deterministic changes: daily, yearly, and encompassing the period of many years [2, 18, 19]. Daily fluctuations involve a characteristic increase in wind speed round noon and its decrease at night. It should, however, be underlined that the changes mentioned above are not fully repetitive and merely constitute a reflection of typical weather phenomena connected with the effect of the Sun [12]. Annual changes are connected with the changing seasons of the year: in the autumn–winter period, the average monthly value of wind energy is higher than the value for the spring–summer period, and the differences can reach between 30% and 40% [15]. Fluctuations over the period of many years result from long–lasting climate change and, on the basis of research performed in wind power plants in the Danish system [9, 11, 20], they are periodic. The trend of those changes may be determined only on the basis of measurements performed over many years with the use of time series processing mechanisms, e.g. mechanical levelling or regression methods [13, 14].

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